FLOATING BREAKWATER AND PROPULSION SYSTEM

Background

The present invention relates to a breakwater device and to a propulsion system.

By definition a breakwater creates an area of calmed water behind it by reflecting, scattering or absorbing energy from the waves.

Existing breakwaters have varied in their design and complexity. One example of a very simple breakwater is a sandbar or embankment on which rocks may be deposited. Such breakwaters may be reinforced using groynes and/or concrete piling.

Prior Art

An example of another type of breakwater device is described in published UK patent application number GB-A-2370594 (Kepner Plastics Fabricators Inc) and describes an elongate sealed envelope containing a liquid and pressurised air. The breakwater is adapted to float. By varying the amount of internal pressure the breakwater can be arranged to attenuate waves.

A disadvantage with the aforementioned breakwater has been that it is relatively complex to manufacture and therefore has proven quite expensive. Also, due to the relatively high internal pressure of fluids and the nature of the flexible material, it has been prone to puncture. This has entailed maintenance on a regular basis. It is also (as with all other known breakwater devices) inertia dependant, that is to say, the mass of the breakwater must be similar to that of the largest waves that it repels. This further adds to the overall cost.

The present invention stems from some work aimed at overcoming those disadvantages of existing breakwaters, by providing a simple breakwater device, having relatively few moving parts, which is not inertia dependant, which absorbs rather than reflects or scatters wave energy, which generates minimum mooring loads and which may be fabricated, transported and assembled cheaply and easily.

A particular advantage of a breakwater, in accordance with a preferred aspect of the present invention, is that it can be relatively cheap to manufacture and maintain, and relatively light in weight.

Summaries of the Invention

According to one aspect of the present invention I provide a breakwater device in which one or more energy absorbers are arranged between a plurality of submerged floating structures and adapted to remove wave energy from the relative motion of the structures and opposing forces which are created between these structures by virtue of the fact that the structures are located in different parts of the irrotational oscillating process of the water mass which occurs naturally during the passage of waves.

Preferably the floating structures comprise first and second structures, which in use are arranged substantially parallel one to another, said first and second structures having neutral buoyancy, and an energy absorber device mounted therebetween, whereby in use, the device absorbs energy from forces and displacement of the first and second structures relative to one another when impinged upon by an incident wave.

The invention is therefore not reflecting or scattering the wave energy, as has been the case with existing breakwaters, but rather is absorbing energy by virtue of the relative displacement between displaceable structures.

The expression neutral buoyancy is intended to encompass anything that does not sink. Neutral buoyancy can include articles that float, partially float or can be made sufficiently buoyant so that they are submersible, but still float. For example, an object of neutral buoyancy includes one that is lightweight (and naturally floats) and has been weighted with a ballast; or one that naturally sinks and has been made buoyant so that it floats.

Ideally the first and second structures are planar and arranged parallel one to another, when viewed from a perspective of the direction of an incident wave. Advantageously they are positioned in an area of open sea so that the major plane of each of the structures is substantially orthogonal to the incident wave front.

Optionally a mechanical interconnection connects the first and second structures; the interconnection preferably comprising means for supporting the energy absorber.

The mechanical interconnection may, for example, be a sliding link.

The interconnection may be substantially straight or of arched or generally calliper shape.

The energy absorber is preferably supported between the structures and is adapted to absorb energy resulting from relative displacement of the

structures towards one another as well as apart from one another and the forces which occur thereto.

The energy absorber may be supported in the body of the liquid or above the surface of the liquid through which the wave is propagating, but is advantageously supported between the structures within the body of the liquid supporting them.

The energy that is absorbed may be extracted and used to drive a generator for producing an electric current, pump water or do another form of work, or could be used to drive a propulsion system for use by the device itself. By definition absorbing of the wave energy will create a calmed area of sea which can be used to provide protection on the leeward side of the device from the waves. Such a device may be incorporated in a myriad of situations.

Preferably the breakwater device comprises three substantially planar structures, arranged substantially parallel one to another. Ideally the distance between the first and second structures is substantially twice the distance between the second and third structure. Ideally the distance between the first and third structures is approximately $\lambda/2$, where λ represents the maximum wavelength of waves in the particular location where the breakwater device is to be deployed. The distance between the first and third structures should be capable of varying by at least 2x the maximum wave height about the nominal spacing of $\lambda/2$ of waves of wavelength λ.

The distance between the first and second structures should be nominally 2/3 the distance between the first and third structures (ie $\lambda/3$) and should be capable of varying by at least 2x the maximum wave height about the nominal spacing of $\lambda/3$ of a wave of wavelength $2\lambda/3$.

Likewise the distance between the second and third structures should nominally be half that of the distance between the first and second structures and the distance between the second and third structures should be capable of varying by at least 2x the maximum wave height of a wave of wavelength $\lambda/3$. This particular combination of these relative distances has been found to provide effective energy absorbing qualities and is very well adapted at absorbing a myriad of wave lengths, of principal wavelength λ downwards.

A further mechanical interconnection can be provided to link the second and third structures, and this interconnection may support a further energy absorber.

A plurality of such breakwater devices may be arranged so as to create a breakwater system. Such a breakwater system may be used, for example, to maintain or modify coastal deposition and/or erosion patterns. Other uses of a plurality of breakwater devices, hereinafter referred to as a breakwater system, are explained later.

Ideally the plate like structures are substantially parallelepiped in shape and external appearance. However, the structures may be ovaloid or ellipsoid, provided they present a substantially large surface area to an incident wave. The definition of a parallelepiped plate like structure is hereindefined as: the ratio between the area of the plate like structure, which is presented to the direction of a wave, and the square of the thickness of the plate like structure. Ideally this ratio should be in excess of 10, preferably in excess of 20 and ideally in excess of 30.

Plate like structures may be formed from a variety of materials or composites. What is important is that the structure formed is able to float, or it may be modified to have neutrally buoyancy, and the structure

is strong. Ideally structures are able to withstand compressive and bending forces imposed by the action of incident waves, as well as occasional impacts with buoys and sea life.

An example of a suitable material is reinforced glass fibre. Other examples are mild steel, flexible concrete or wood. Other materials may be used and it will be apparent to a skilled artisan what types of materials and their respective dimensions, depending upon the particular environment in which the structures are to be deployed and prevailing weather, sea and other conditions.

Due to the fact that the majority of energy transmitted via wave action appears relatively close to the surface of water, through which the wave progresses, there is relatively little energy apparent below a depth of about one third to a half of a wavelength ($\lambda/3$-$\lambda/2$). Therefore the height of the plate like structure is ideally less than half a wavelength ($\lambda/2$) of the prevailing wave conditions (and preferably less than $\lambda/5$) of the sea area where the breakwater device is to be deployed. The length and width of the structure is dependent upon, amongst other things, the strength of the material used to fabricate the structure and the depth of the local sea.

The energy absorber acting between adjacent plates may take one of a variety of forms. For example, the energy absorber may be a water choke arranged to squeeze water through a throttle so as to dissipate energy. This is a simple but effective manner to remove energy from waves. What is most desirable is that the energy absorbers should not contain any storing capability, such as a spring, as this could give rise to resonance of the breakwater device, with the result that energy is temporarily removed (stored) and reflected back into the water, rather than being permanently removed from the system and all energy

removing devices must be capable of removing energy as plates move towards one another as well as when they move apart. In this way the requirements of Bernoulli's theory of irrotation are satisfied with forward and reverse forces within the wave cancelling each other out whilst energy is extracted and only a nominal "second order" external reaction being created. The device therefore being arranged to generate small mooring loads.

One way of achieving energy absorption is with an electromagnetic arrangement, sealed inside suitable waterproof containers, configured to present a resistive force against relative displacement of the plate like structures resulting in generation of an electromotive force.

A rack and pinion arrangement is another way in which energy can be removed. The rack and pinion may be fitted with suitable gears to transmit incident energy to a rotating resistive force, so that the energy of a wave can be extracted.

A yet further example of an energy absorber is a piston in cylinder arrangement acting as a dashpot. Alternatively the energy absorber may comprise a piston in cylinder having a fluid with variable rheological properties.

Another type of energy absorber is a bi-directional hydraulic pump, which is adapted to remove energy during relative displacement of adjacent plates towards one another and away from one another. In a preferred embodiment, using this type of energy absorber, two non-return valves are arranged at each end of a cylinder containing a bi-directional piston which itself is connected to adjacent plates. Relative motion

between the adjacent plates moves the piston in either direction which in turn pumps fluid at high pressure out of the relevant non-return valve at one end of the cylinder and draws fluid in at the other. In this way energy in the form of fluid at high pressure is continuously extracted from the wave system and delivered to an external storage or use system regardless of the direction of motion of the adjacent plates. All that is required is relative motion to occur. Again however, it is important that no compressible fluid is used as this could act as a pneumatic spring re-injecting energy back into the wave system.

Advantageously a plurality of these devices can be interconnected, in the form of a loosely coupled barrier, so as to provide a breakwater system. Due to the nature of the energy absorbers little relative displacement or external reaction is experienced between adjacent devices. This means that only modest tethering or anchoring of such a breakwater system is required.

When suitably modified, as described below, such a breakwater system could also be used as a propulsive means for example to tow or salvage seagoing vessels, with the possibility of providing a benign wave climate around the vessel.

According to a second aspect of the invention I provide a propulsive device for use in a body of water comprising first and second submerged structures arranged substantially parallel to one another and connected by a strut, the first and second structures both comprising non-return valve arrays, which arrays permit water to flow in a substantially horizontal direction through the respective array in one direction, both arrays being arranged to be operable in the same direction whereby when the device is orientated generally orthogonal to the incident wavefront with the structures spaced apart by approximately half a wave length of waves in

the body of water, the natural irrotational oscillation of the water mass acts in the reverse direction onto the one valve array compared with the other.

Thus, in the propulsion mode the structures are desirably held a fixed distance approximately half a wave length apart to take best advantage of the maximum difference in water mass oscillation occurring in the trough as opposed to the crest of the wave.

We are aware of patent specification number US 3222870 which discloses a breakwater structure comprising at least three louver valve assemblies spaced horizontally apart. However, in these assemblies the valves are arranged such that those of a first, seaward assembly always open in the opposite sense to the valves of the final, shoreward assembly. This breakwater construction uses the louver valves to 'trap' waves and so destroy their natural motion. In contrast, the present invention comprises two louver valve assemblies in which the valves of the first and second assemblies always open in the same sense. The present invention utilises the natural motion of the waves to create a propulsive motion.

The system may however be used in both energy absorption and propulsion modes at the same time. However, limitation of both effects would be required to maintain a balance between the two modes.

Automatic operation of the non-return valves, by the oscillating motion of the water mass enables the energy of waves to be harnessed to provide a driving force. For example it will be appreciated from Bernoulli's theory of irrotation, that a displacement in a direction opposite to the direction of the wave can be obtained in the wave trough. This force may be harnessed from several devices and used, for example to retrieve ships which have run aground against the direction of the prevailing waves or

even as a propulsive means for a vessel in the event of, for example, engine failure.

Alternatively control means can be included which is operable to open and close or change the manner of operation of the valves in the structures.

According to further aspects of the invention there is provided means to protect multi-hulled craft, such as a catamaran, and provide means to protect long vessels (which during passage may inadvertently straddle in a diagonal fashion more than one wave). Protection is therefore provided by an embodiment of the invention for multi-hulled craft, by exploiting and allowing the relative motion between the hulls to occur. Additionally the invention may provide means for protecting long vessels, structures, or other items which are endangered by submerged oscillation occurring within a water mass, by articulation or double articulation to allow transverse differential motion to occur along the length.

Brief Description of the Drawings

Preferred embodiments of the invention will now be described, by way of example only, and with reference to the accompanying drawings in which:

Figures 1 and 2 illustrate diagrammatically how energy, in the form of waves passing through a body of water affects and moves submerged bodies;

Figures 3a to 3d illustrate diagrammatically how breakwater device walls, according to a first aspect of the invention move relative to one another during the passage of waves of wavelength twice the distance between them;

Figures 4a to 4d illustrate diagrammatically how wave energy is transmitted and can be absorbed by the device as illustrated in Figures 3a to 3d when an energy absorbing system is placed between the walls.

Figures 5a to 5d illustrates diagrammatically how by adding a third wall and associated energy absorbing device to the system illustrated in Figures 4a to 4d wave energy can be absorbed by a myriad of different wavelengths at the same time constituting a complex sea state.

Figures 6a to 6d illustrate diagrammatically how an embodiment of the invention can use wave energy to produce propulsion into or with the direction of travel of the waves.

Figure 7 is a diagrammatical representation of an embodiment of the breakwater device using a simple water choke to absorb the wave energy.

Figure 8 shows operation of a plurality of breakwater devices arranged as a breakwater system for protecting coastal regions and/or managing coastal erosion and deposition.

Figure 9 is a diagrammatical representation of a breakwater system for salvaging and protecting vessels.

Figure 10 is a diagrammatical plan view of an alternative aspect of the invention in which a plurality of propulsive devices are shown in diagrammatical form, towing a vessel;

Figures 11 and 12 illustrate diagrammatically irrotational oscillation of a body of water and how this motion is affected by water depth in relation to wave length;

Figures 13a to 13c illustrate diagrammatically how a device, according to a yet further aspect of the invention, is capable of accommodating relative motion occurring in different parts of a waveform in accordance with Bernoulli's theory of irrotational motion to prevent damage to a multi-hulled vessel;

Explanation of Theory on which the Invention is based

Referring to the Figures 11 and 12, and particularly Figures 1 and 2, there is depicted a diagrammatical series of images, which explain how energy progresses through a body of liquid. This has been included as it provides a useful explanation to assist the reader with the theory on which the invention relies.

Physics demonstrates that energy is transmitted through a body of water by means of a submerged oscillatory motion of the water mass about a relatively fixed datum. The fixed datum moves only gradually in the wave direction. This motion is known as an irrotational oscillation but can be referred to as "wobbling". The wobbling motion is both up and down, as well as back and forth, and creates a coherent circular or elliptical oscillating, "wobbling" pattern about a point. The point is substantially stationary relative to the seabed. A phase shift between the vertical and horizontal oscillations determines: the direction of "rotation" of the oscillating pattern; the direction of travel of the progressive waves on the surface; and the transmission of energy in that direction. The presence or absence of this "wobbling" motion is the only difference between still water and that which has waves passing across it.

The coherent oscillatory motion of the water mass extends downwards from the surface, reducing exponentially in amplitude to about 5% of its size at the surface at a depth of 1/2 wavelength (λ/2). The oscillatory motion in the water is phase dependant. That is to say, when it is oscillating in the wave direction, it creates a crest and when it is oscillating against the wave direction it creates a trough. The momentum, force applied and distance travelled by the coherent mass of fluid in the wave is substantially the same in all directions, with fluid particles returning to almost the same position, relative to the datum, at the end of each cycle. The wave profile and it's motion across the water, therefore, only represents the transmission of energy through the water and not the motion of the water mass itself.

It can be shown that wave energy is transferred only by the difference in potential energy (height) of the coherent water mass when oscillating with the wave direction at the crest to that of the same water mass when oscillating against the wave direction in the trough. The fluid motion described is in accordance with the Bernoulli steady state integrated equation of motion and assumes irrotational flow and invariant fluid density throughout the bulk of the fluid. This theory therefore underpins the primary mechanism of energy transfer through water in the form of waves and is the theory on which this patent is based.

Figure 1 represents the oscillating motion of a "discrete" block of water 3 (shown hatched for clarity), during the passage of a wave 2. For the purpose of explanation only, impermeable, infinitely thin and flexible diaphragms 4 and 5 can be imagined to be positioned at the front and rear boundaries of this discrete block of water, so that its VOLUME, MASS AND IDENTITY remain the same throughout the process. During wave transit this mass oscillates back and forth, yet remains approximately in the same position relative to a fixed seabed datum 16. The diaphragms 4

and 5 bend backwards and forwards not in phase with each other, but respectively in phase with that part of the wave profile that is passing across that part of the surface of the water. As well as swaying backwards and forwards relative to the datum, this discrete block of water becomes taller and narrower (as shown in Figure 1c) and shorter and wider (as shown in Figure 1a) in a sequential and oscillating "wobbling" manner as each wave cycle passes.

During this process a floating vertical plate like structure 7 will move backwards and forwards relative to the datum 16, by a total distance (measured at the water surface of approximately the wave height. The plate itself, however, has minimal effect upon the passage of the wave, and is virtually transparent to the passage of the energy.

A buoy 1, floating on the surface of the water transcribes a circle about the datum 16 of diameter approximately equal to the wave height. However, the buoy 1 does not itself rotate. This type of fluid motion is called an irrotational oscillation.

From Figure 1 it can be seen that the oscillation of the block represents cyclic motion of a large volume and therefore large mass of water a total distance at the surface of approximately the wave height every wave cycle in the horizontal direction. The kinetic energy and momentum of this block of water is also large, being a measure of the total quantity of energy, which is contained within the wave. If the horizontal motion of plate 7 is resisted, the whole oscillating mass of the water reacts on it and generates large forces in the process. Since this is an oscillating process, the direction of action of the forces reverses twice during the passage of each wave cycle. For this reason vertical plates positioned one

wavelength apart are always acted upon by forces and displacements in the same direction. However, plates, located half a wavelength apart, will always be acted upon by equal forces and displacements in opposite directions. This phenomenon is shown by the direction of arrow 8 in Figures 1a and 1c.

As mentioned above, the oscillating process occurring in the body of water is not restricted to the horizontal direction. Oscillation occurs in the vertical axis during the same time interval. This results in a circular or even elliptical complex oscillating motion. Figure 2 shows how numerous plate like structures 10, located in different parts of a water mass, which is oscillating and causing the passage of waves 2 overhead, all experience different parts of the oscillating cycle at any instant in time. The part of the cycle experienced by a plate depends upon its position relative to the part of the wave passing overhead. Also, as the depth at which plates are located increases, the size of the oscillation excursion reduces until below a certain depth it tends to disappear. Therefore each of the plate like structures move relative to other structures located in different parts of the water mass as the waves pass overhead and their distances apart are continuously changing. The one exception to this is if plates are positioned exactly one wavelength apart in the horizontal direction as detailed above. The orientation of these structures however will not substantially change during the oscillation process. That is to say end B of structure 10 continues to point to the right throughout its circular, orbital path.

Figures 11 & 12 show how these motions apply to vertical plates 56 suspended in deep water where depth > $\lambda/2$ Figure 11 and shallow water where depth < $\lambda/20$ Figure 12. In Figure 11 the motion of the top edge of the plate (in this case suspended by a buoyancy device 60) is approximately circular, of excursion approximately equal to wave height

about seabed datum 54 and clockwise with respect to waves 52 approaching from the left. The horizontal motion of the bottom edge of the plate is reduced in amplitude as explained earlier but the vertical excursion (being controlled by wave height) is the same as the top edge and this results in a vertical elliptical motion of the bottom edge. Figure 12 demonstrates how the plate motion changes in shallow water. Here the motion of the top edge of the plate is elliptical with a vertical excursion axis of approximately wave height and a rotation clockwise in relation to waves 52 approaching from the left. The motion of the bottom edge of the plate is again the same in the vertical direction but much magnified in the horizontal direction thus resulting in the elongated horizontal ellipse as shown.

Detailed Description of Preferred Embodiments

Figure 3 shows an example of an embodiment of the invention that could extract energy from a wave. This device 12 comprises first 13 and second 14 floating vertical structures arranged substantially parallel one to another. Structures 13 and 14 are spaced nominally half a wavelength apart. The device 12 is oriented in use, so that the planes of structures 13 and 14 substantially orthogonal to the general direction of waves. Structures 13 and 14 are coupled together by a device 15. The device 15 may be an energy absorbing double acting hydraulic pump, but in this example it is allowed to move freely in and out without extracting any energy.

In this configuration an embodiment of the invention is envisaged under conditions whereby tilt, stroke and distance measuring devices are incorporated into the device 15 to accurately measure wave height, wavelength and wave period. Further to this, delicate equipment (or personnel) located and supported approximately midway between plates

13 and 14 are subjected to only a minimum degree of lateral or vertical motion relative to the seabed.

As explained in Figure 1, a floating vertical plate like structure can be shown to oscillate backwards and forwards about a datum a total distance of approximately one wave height during the passage of each wave cycle.

Figure 3a shows how structure 13 is behind datum 16, as a wave trough passes and a wave crest approaches whereas structure 14 is in front of datum 17, as wave crest passes and wave trough approaches. The two structures 13 and 14 are therefore further apart than their nominal spacing, by about one wave height at the instant shown in Figure 3a. Likewise, as the progressive wave profile passes, structures 13 and 14 move two wave heights closer together. This is shown in Figure 3c. Since the datums 16 and 17 are fixed, both relative to each other and the seabed, the structures 13 and 14 move relative to each other a distance of approximately two wave heights. This occurs each wave cycle. However, it will be noted that the assembly remains substantially stationary relative to the seabed.

Motion is symmetrical about datums 16 and 17 when no energy is being extracted by device 15. In this condition plate like structures 13 and 14 are free to move backwards and forwards solely under the influence of oscillating water mass and the waves proceed virtually unaffected as explained above with reference to Figure 1.

Figures 4a to 4d show how wave motion changes when energy is being extracted by pump 15. In this example progressive waves 2 are considered to approach from the left. Extraction of energy by the pump 15 means that relative motion must occur between plates 13 and 14 against a force f. It also follows that the external forces transmitted by

plate 14 into the water (on its right hand side) and its motion (relative to datum 17) must always be zero or wave energy would be transmitted and lost.

Figure 4a shows how the extraction of energy by pump 15 through the application of a force -f causes a reduction in trough depth 18 across plate 13 (In this description forces and motions to the left ie against the direction of travel of the waves are considered as negative and forces and motions to the right that is to say with the direction of the waves are considered to be positive although the exact opposite notation would work just as well). During this process plate 13 moves a distance –d to the left that is to say with the oscillating mass of water and the force times the distance means that a positive amount of energy +W will have been extracted from the wave.

In Figure 4a this motion is to the left because the direction of oscillation in a wave trough is in the opposite direction to that of the wave itself. Because plate 13 is moving, it transmits a progressive "in phase" wave into the space between plates 13 and 14 and this has the same wavelength as the incident wave. However, its trough and crest amplitude are reduced in direct relation to the quantity of energy remaining from that extracted by the pump 15. The reduction in wave energy means that the oscillating motion within the wave is also reduced. This is shown as a reduction in deflection of "imaginary" diaphragms for example from position 19 shown dashed to the lesser deflected position 20 shown solid.

As mentioned earlier, plate 13 must apply a force to the pump 15 as well as move relative to it so as to enable energy to be extracted. The equal and opposite reaction to this force however appears on plate 14 and this would cause it to be moved to the left and generate a wave trough to its right, if it were not resisted by an equal and opposite force to the right.

From the previous description of the oscillating motion within the waves, it is apparent that the direction of motion of the forces, within the wave, are reversed every half cycle. Therefore if plates 13 and 14 are positioned nominally half a wavelength apart, plate 14 will be acted upon by a force to the right which counteracts the force generated by pump 15.

In closer examination it is apparent that the level (energy change) across plate 13 must always be equal and opposite to the level (energy change) across plate 14 at all times, as action and reaction across the pump 15 must always be equal. The "level" change across plate 13 is thus replicated in reverse by the "level" change across plate 14, whereas the degree of level change is determined by the quantity of energy extracted by the pump 15. Different amounts of energy extracted produce different effects from these level changes. For example, if only a small percentage of the available energy is extracted, the level change 18a would be small in relation to the trough depth 24. Because this is replicated in reverse on plate 14, the level change 21a would also be small in relation to (intermediate) wave crest height 26. The reverse reaction force (generated on plate 14 by pump 15) is therefore not large enough to resist all of the force generated by wave crest 26. Any unresisted surplus 26a moves plate 14 to the right, transmitting some of the wave energy through to the right of plate 14 which is therefore transmitted through the system and lost.

If however the backpressure on pump 15 is increased the level (energy change) 18 across plate 13 correspondingly increases. The effect is that the transmitted wave trough depth 27 is reduced since the impinging trough depth 24 does not change. However, the trough depth 27, also determines the crest height 21, since they are both functions of the same reduced amplitude oscillating process. Thus, as the level difference 18 is increased, with increased backpressure from the pump 15, both the

remaining trough depth 27 and the remaining crest height 21 reduce correspondingly. At a certain level of energy extraction (back pressure) the "level" difference 21a across plate 14 will match the still water level 22. Under these conditions there are no residual forces remaining on plate 14 to create a wave on its right hand side and therefore no horizontal motion occurs. The wave has therefore theoretically disappeared because the pump 15 has extracted all the oscillating energy entrained in it.

To assist in explanation the phrase "level" (energy change) has been used to define the different states occurring across the plates. This is because the energy in a wave is not directly proportional to its height but to the square of its height. Therefore directly measured height differences across the plates have to be mathematically computed using a square law to compare them with changes of energy. Secondly the shape of "real" waves is approximately Stokian and not sinusoidal. That is to say the steepness of curve is greater over wave crest 28 than it is through wave trough 29, as can be seen in Figure 4b.

Figure 4b shows how wave trough 31 is longer than wave crest 30 as measured along the mean "still" water line and demonstrates how, as the progressive waves pass, the natural motion of plate 13 as it moves back and forth will follow the point where the still water level intersects the wave surface profile.

Figures 4a to 4d show the motions of a wave 2 and plates 13 and 14 throughout a full progressive wave cycle. From this series of "snapshots" it can be seen how balancing and cancelling of wave forces continues throughout the process. For example in Figure 4b, as wave crest 2 approaches from the left, both plates 13 and 14 coincide with a wave "node" point; and therefore level differences (i.e. forces) across

both will disappear. Between states Figure 4a and 4b trough depth 27 progressively decreases at the same rate as the crest 21 reduces thus maintaining a state of equilibrium and force balance. Between Figure 4b and 4c the wave crest approaches plate 13, generating a wave trough against plate 14, which provides a reaction force to counteract the crest force acting on plate 13. Figure 4d shows the situation has returned to that of Figure 4b but in mirror image. As the progressive wave continues the configuration of Figure 4a returns and the process repeats continuously in a cyclic manner.

Two fundamental properties of the device can now be defined from the forgoing analysis. Firstly, plates placed one wavelength apart oscillate in a circular or elliptical pattern relative to the seabed, but in unison and without measurable differential motion between them. Secondly, plates placed half a wavelength apart oscillate in the same pattern, but diametrically opposed to each other, and create a differential motion approximately equivalent to two wave heights each wave cycle at the sea surface.

When the plates are positioned one wavelength apart, and fixed together, wave energy passes right through the device virtually unaffected; whereas when the plates are positioned approximately half a wavelength apart, or $(n+1/2)\lambda$ wavelengths apart where n is a positive whole number including zero, theoretically energy can be extracted up to a quantity equal to the total amount available in the wave, by adjusting the resistive force (back pressure) of an energy absorber adapted to extract energy from the relative displacement occurring between the plates.

A further embodiment of the invention is now described with reference to Figure 5 wherein vertically orientated floating plates 32, 33 and 34 are positioned orthogonal to the general direction of the waves and coupled

together by two double acting hydraulic pumps 30 and 31. Plate 33 is nominally located 2/3 and 1/3 from outer plates 32 and 34 respectively. This embodiment has been found to be capable of extracting wave energy from a wide range of wavelengths.

Figure 5b shows how plates 32 and 33 move in a similar manner to plates 13 and 14 of Figure 4, when acted upon by waves of wavelength of the order of twice the distance between these plates. As explained above, with reference to Figure 4, theoretically substantially all the energy contained within the wave can be absorbed. Plate 34 is then effectively redundant. If the device is now acted upon by waves of shorter wavelengths, for example of wavelength equal to the distance between plates 32 and 33, as shown in Figure 5c, then plates 32 and 33 move backwards and forwards in unison allowing the waves to pass "through" unimpeded. Plates 33 and 34, however, which are positioned half the distance apart of plates 32 and 33, are now at the correct spacing of $\lambda/2$ to absorb all the wave energy via pump 31.

In fact wave energy can be extracted with maximum efficiency by the device from any wavelengths λ where the plate spacing is $\lambda(n + 1/2)$ between any two plates and n is a positive full number including zero. Thus for example spaceings of $\lambda(0 + 1/2) = 0.5\lambda$, $\lambda(1 + 1/2) = 1.5\lambda$, $\lambda(2 + 1/2) = 2.5\lambda$ etc between any two plates provide maximum energy absorption. In between these specific wavelengths the function of energy extraction is divided between different pairs of plates; an example of which is shown in Figure 5a. In this situation the exact half wavelength exists between plates 32 and 34. However, because plate 33 is located 1/3 wavelength from plate 34, a small proportion of the wave energy is extracted by pump 31 with the remainder being extracted by pump 30. This works because each plate only "sees" the horizontal differential motion occurring between it and the other two plates and extracts energy

from this motion to an amount equal to (displacement) x (the resisting force). In this way wavelengths, where the half wavelength does not exactly equate to any of the plate pair spacing, still achieve a high energy extraction efficiency. For example a wavelength equal to the distance between plates 32 and 34 cannot extract any energy from this pair, but only from intermediate plate 33, which is now a maximum of 1/6 of a wavelength offset from the nominal 1/2 wavelength position.

This creates a small, but not significant, drop in energy extraction efficiency at this wavelength. Energy can also be extracted from wavelengths, which are shorter than the distance between plates 33 and 34 and Figure 5d shows how using equation $\lambda(n + 1/2)$ enables a maximum energy absorption to be achieved with much shorter wavelengths.

Further to the above, real seas invariably comprise combinations of wavelengths creating a complex surface shape and pattern and this is the most common form usually encountered. As previously explained the shape, (which in this case can be more accurately described as the velocity and elevation of a particle at any instantaneous point on the surface), defines the single motion occurring at that point under the surface which has been created by the sums and differences of all the waves of different lengths passing through that point. The proposed embodiment of this invention employs this resultant differential motion, effectively extracting energy from all of the entrained different wavelengths, as if they were individually isolated one from the other. Further embodiments of the invention are now described with particular reference to Figures 6 to 10 and Figure 13.

Aspects of the invention will be described with reference to: i) extraction of energy from waves; ii) marine propulsion using energy derived from

waves; and iii) mitigation and compensation of destructive forces occurring between multi-hulled vessels.

Figures 6a to 6d show how the horizontal oscillating forces and motions occurring within a water mass can be used to provide a means of propulsion both into and with the direction of the waves. Embodiments of the invention employing this principle are shown in Figures 9 and 10.

Figures 6a to 6d, show the diagrammatic representation of a propulsion device that comprises two sets of vertically, oriented floating "louver" valves or arrays of louver valves 51 and 52. These valves allow water flow in the same direction only (in this case to the right) and present a solid impervious wall to water flow in the opposite (left hand) direction. The two louver valve arrays are coupled together half a wavelength apart by a fixed length connector 53 pin jointed to the arrays at both ends and are arranged orthogonal to the general direction of progressive waves 2 which in this example are considered to be approaching from the left.

Figure 6b shows how two "discrete" blocks of water 54 and 55, shown hatched for clarity only, are moving in an irrotational oscillating manner during the passage of a wave overhead. Block 55, in the trough, is oscillating generally in the direction of arrow 56, that is to say in the opposite direction to that of the wave crest. This shuts the louver valves and pushes array 52 to the left. At the same time the louver valve array 51, which is a fixed distance of half a wavelength ahead of valve array 52, is acted upon by block of water 54, which is oscillating with the crest generally in the direction of arrow 57. This opens the louver valves and allows the mass of water to pass through the array. The whole device is therefore displaced a distance of approximately one wave height 58 to the left during this process, as can be seen from Figures 6a,

6b and 6c by the force generated by the momentum of the oscillating mass of water 55.

In Figure 6d, as the process continues, louver valves 51 shut under the action of the mass 54 oscillating to the left in the trough and louver valves 52 open to allow the mass 55 through as it oscillates with the crest to the right and the device continues to be displaced to the left. In between positive horizontal displacements occurring at Figures 6b and 6d the irrotatonal oscillation of the water mass is mainly in the vertical direction. For example in Figure 6c water mass 54 is oscillating mainly downwards and water mass 55 is oscillating mainly upwards, however because of momentum, the device continues to move to the left and both sets of louvre valves 51 and 52 open allowing "vectored" relative motion of both water masses to pass through the valves. A similar situation occurs at Figure 6a, but in mirror image. The situation then returns to Figure 6b and is repeated in a continuous cycle.

The above description of the method of propulsion has been arranged to show how it can operate in the opposite direction to that of the waves because this offers the most unique properties. However, this method of propulsion can operate just as well with the waves simply changing the direction of operation of the non-return louver valves. For example the valves are now closed and are driven to the right at the crest, whilst the valves on the other set are open through the trough. In this way propulsion is equally effective with, as well as against, the direction of the waves. This propulsion is created by what is known as "first order wave effects". However, second order wave effects will generate a percentage overall mass drift of the water in the direction of travel of the waves (for example 15%) which means that in reality the speed of motion of the device, with respect to the seabed, is about -15% of the mean speed against and about +15% of the mean speed with the wave

direction. It will be appreciated that sets of louver valves may be controlled to operate in either or both directions so that the device may be propelled to the left or the right. It will also be appreciated that rudders could be attached to the arrays to enable "tacking" at an angle to the wave front with or against the wave direction and that an energy absorbing device of the type outlined in Figure 4 could also be fitted between the arrays which together with propellers or other types of propulsion means be used wholly or in part to provide propulsion at right angles to the wave fronts or any combination angle thereto. It is accepted that the use of two arrays can mean the use of any number of associated arrays.

Figure 7 shows an embodiment of a breakwater device having two rectangular plates 100 and 102 and an energy absorber 104 pivotally mounted to each plate by pivots 108 and 110. The energy absorber is submerged and comprises a loose fitting piston or flow restricting device 111 located in a cavity 112 which has a loose fitting aperture 113 and choke passage 114. In operation differential motion between the plates during the passage of waves causes motion of the flow restricting device 111 and water to be forced in and out of cavities 115 and 116 and also past the flow restricting device creating a resistive force both when the plates are moving apart and together thereby extracting energy from the waves.

Figure 8 shows an alternative embodiment of the invention, in which a plurality (in this case eight) floating devices 205 and 206 (as described in more detail in Figures 4 and 5) are linked together in the form of a chain so as to provide a breakwater system to protect the shoreline 207. Waves are present in the open sea 200, whereas the water surface 210 in the lee of the breakwater system is calm as a result of energy having been absorbed by the breakwater system. In this embodiment two or three

plate arrays could be grouped to deliberately adjust the wave climate to manage coastal erosion or deposition patterns on the shoreline 207.

Figure 9 is a diagrammatical representation of an alternative aspect of the invention wherein a plurality of propulsive devices 232, (as described in more detail in Figure 6), are acting together to tow a stranded vessel 250 from rocks or running aground on a sandbar. In the process of extracting energy from the waves 233 to tow the vessel, the waves are reduced thus creating a more calm sea state 234 for protection of the vessel whilst the salvage operation is in progress.

Figure 10 is a diagrammatical representation of a propulsive system for salvaging or towing vessels. Ship 220 deploys or uses devices 222, 224 and 226, (as described in more detail in Fig 6), to provide propulsion for the ship in the direction of arrow 229 in the event of engine failure or to conserve fuel. Energy extracted from the waves 227 to provide the propulsion will create a more calm sea area 228 in which the ship is located. The devices may be stored flat for example on the deck of a ship for use in an emergency.

Further applications of this invention are perceived, which do not involve solely the extraction of energy or methods of propulsion, but which utilise the underlying principle of irrotational oscillation within the water mass. One such example is the use of the invention in catamarans and other types of multi-hulled craft to prevent or inhibit strange and unpredictable handling characteristics in certain types of seas and to prevent additional high side loads being applied to the hulls. This applies particularly to catamarans, which have narrow, and deep widely spaced "wave piercing" hulls used mainly for speed and performance.

In this embodiment of the invention means is provided to enable the two hulls of a catamaran type craft to move in and out in a parallel way relative to each other a distance of at least two wave heights thus allowing the hulls to follow the natural oscillating process occurring within the water mass and preventing these loads being transmitted to the main structure. The process is described briefly below.

Figures 13a to 13c show how the aforementioned principle may be employed.

Figure 13a shows a wave-piercing catamaran with hulls that are floating in "discrete" blocks of water 62 and 63 and joined together with sliding interconnect 64. Figure 13a depicts the situation when no waves are present and therefore there is no irrotational oscillation in the blocks of water. Figure 13b shows the situation that prevails when the trough of a progressive wave 68 (whose wavelength is approximately twice the distance between the hulls) passes. The attendant irrotational oscillation of the submerged water mass moves the two hulls further apart by a distance of approximately one wave height. Figure 13c depicts the situation where the crest of the progressive wave passes across the hulls. Here the irrotational oscillation of the submerged water mass now moves the two hulls closer together by a distance of approximately one wave height. Therefore between the situation depicted in Figure 13b and Figure 13c, as progressive wave 68 passes, the water mass oscillation pulls the hulls apart and pushes them together a total distance of approximately twice the wave height each wave cycle. In operation the allowable variations of distance between the hulls accommodated by the sliding interconnect 64 compensates and fully accommodates the displacement caused by the mass moment oscillation of the water during the passage of waves. This prevents damage from lateral forces acting onto the sides of the hulls and connecting bridge of the craft.

Additionally means may be provided to allow a "serpentine" effect to occur between the hulls to follow the oscillating water pattern thereby ensuring that the hulls are always travelling at right angles to the local oscillating pattern to attain maximum penetration efficiency. A twin hulled craft as previously described, with a fixed bridge and subjected to a side sea whose wavelength is approximately twice the distance between the hulls experiences large, possibly damaging forces between these hulls created by this mass moment of the waves operating in opposite directions on each of the two hulls at the same time.

In a further embodiment, the interconnect 64 can be replaced by a device which operates to extract energy, both when the hulls are moving together as well as apart, as the twin hulled craft moves through the water. This attained energy can be used in a multiple of ways three of which might be to:-

1. Power auxiliary heat, light, radio equipment etc.

2. Power the craft itself driving it in the direction of the hulls with propellers or other similar mechanical devices or

3. Power the craft using energy retrieved to deliberately create a "serpentine" effect wherein the hulls do not remain parallel but move together and apart differently at the front with respect to the back creating a sculling effect to provide propulsion without the need for further propellers or other similar mechanical devices.

Means can also be employed such as a pantograph or other similar mechanisms to alter the mean distance between the hulls to match the half

wavelength rule to provide maximum energy extraction from the system in differing sea states and wavelengths.

Wave energy absorption, compensating or propulsion means have been described. Plates or plate like structures, positioned in any attitude, provides the effect. The structures may, or may not, allow the passage of liquid therethrough. Valves may be incorporated in the structures so as to allow or facilitate the passage of liquid in one direction. The structures are submerged in different parts of, or below, a body of liquid, which is subject to the oscillating pattern caused by the passage of waves. Ideally wave energy absorption, compensation or propulsion is achieved through the control of the interaction between two or more of the aforesaid structures or between two or more structures interacting against the inertial mass of the body of liquid. This may be enhanced by exploiting, in a controlled manner, the flow of liquid through the structures in one direction only.

Switching on or off a breakwater device can be achieved by manually resetting the distance between its plates. For example moving the plates from half a wavelength to one wavelength apart will switch off the device. Switching off can also be achieved by removing resisting forces from interconnecting means.

The invention has been described by way of exemplary embodiments. It will be appreciated that variation to the embodiments described may be made without departing from the scope of the invention.